2016

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Feichter, Gabriel A.; Groll, Eckhard A.; Kurtulus, Orkan; and Meng, Ben, "Oil Return Measurements In A Unitary Split System Air Conditioner Using Different Refrigerant Mixtures" (2016). *International Refrigeration and Air Conditioning Conference.* Paper 1603.
http://docs.lib.purdue.edu/iracc/1603

Oil Return Measurements in a Unitary Split System Air Conditioner Using Different Refrigerant Mixtures

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ABSTRACT

The aim of the study presented in this paper is an experimental investigation of the oil return characteristics of alternative drop-in refrigerants for residential air conditioning systems using R22. Due to the phase-out of HCFC refrigerants, the production of R22 will be stopped by the year 2020. In some cases, it will be necessary to replace the refrigerant R22 of already installed vapor compression systems with an alternative refrigerant. It may be necessary to change the type of oil used inside the system when retrofitting an existing R22 system with an alternative refrigerant. R22 systems typically use mineral oils and HFC replacement refrigerants use POE or PAG oils. Changing all the oil contained in a vapor compression system is an expensive process due to the required flushing and cleaning steps before refilling the new oil. Therefore, refrigerant manufacturers are searching for alternative drop-in refrigerants, which are compatible with mineral oils and which have similar working performances and properties as R22.

The quantity of the returned oil in the suction line helps to draw conclusions about the ability of the oil properly circulate back to the compressor. In this study, a unitary spilt-system air conditioner with a cooling capacity of 8.5 kW was equipped with an oil separator and an oil-measuring cylinder in the suction line. The experimental test setup was designed and built to measure the mass of oil flowing back to the compressor. Two different compositions of the alternative drop-in refrigerant blends R438 and the refrigerant R407C were tested. The weight of the oil collected in the suction line using the three different compositions are compared with the mass of the oil whilst using R22.

1. INTRODUCTION AND MOTIVATION

The use of the refrigerant chlorodifluoromethane, better known as R22, which belongs to the group of hydrochlorofluorocarbon (HCFC) refrigerants, is regulated by the Montreal Protocol (U.S. Environmental Protection Agency, 2015). After January 1, 2015 the production of only 10% of the U.S baseline is allowed, and after January 1, 2020 only 0.5% will be allowed at which point chemical manufactures will stop producing R22. This makes it necessary to supply existing systems with a HCFC-free refrigerant as a substitute for R22.

Most of the compressors applied in air conditioning systems need oil as a lubricant, which is mostly contained in the oil sump of the compressor. However, a small amount of oil leaves the compressor together with the compressed refrigerant into the refrigeration cycle. To keep the compressor running properly, it is important that the oil circulates throughout the system and returns back to the compressor, otherwise the compressor will run dry over time. Therefore, oil management is a crucial part of the system, necessary to protect the compressor. For small and medium size air conditioning systems it is generally sufficient if the oil and refrigerant are miscible, so that the oil is returned to the compressor with the suction flow.

Replacing R22 in an existing system with an alternative refrigerant can be challenging. For instance, when substituting R22 with R407C in an existing system, it is necessary to change the oil in the system because R407C and mineral oil (MO) are not miscible. A recommended retrofit process to change from R22/MO to HFC/polyol ester oil (POE) requires the following iterative steps: Draining the MO from the system and charge the system with POE and the old refrigerant; running the system for at least 24 hours; test the concentration of MO. Repeat the steps until the concentration of MO drops below 5% (Allied Signal Inc. Genetron, 1995). Only then (after the MO concentration drops below 5%) the new HFC refrigerant can be charged. Such a procedure is time consuming and cost intensive and not feasible for small systems. In the last years, simpler replacement procedures have been recommended, which allow higher concentration of MO in the POE (Honeywell Genetron Refrigerants, 2012).

Some research has been performed to identify the parameters and components, having an impact on the oil return and/or the oil retention behavior in a system.

Cremaschi *et al.* (2004) investigated the oil retention potential for R22/MO and R410A/POE mixtures in the suction line, evaporator, liquid line and condenser. The authors concluded that the oil retention increases when the oil circulation ratio (OCR) is high, the refrigerant mass flow is low, or the liquid film viscosity of the oil is high. It was also shown that the suction line is the most critical component. On the other hand, the oil return was not a problem in the liquid line, where the oil-refrigerant mixture is homogeneously mixed. The difference between R410A/POE and R22/MO in terms of the quantity of the oil flowing back to the compressor was very small.

Cremaschi *et al.* (2005) took a closer look at the behavior of oil return for different refrigerant/oil mixtures. The authors used the same test setup as in Cremaschi *et al.* (2004) including a vertical and horizontal suction line. Five refrigerant/oil mixtures were tested, R22/MO, R410A/MO, R410A/POE, R134a/POE and R134a/PAG. The authors recognized that gravitational effects increase the oil retention up to 50% in a vertical suction line compared to a horizontal line. In addition, the authors found that the very low miscibility and solubility of R410A and mineral oil led to a high film viscosity, which strongly affected the oil retention. R410A/MO showed the highest oil retention of all tested mixtures. Cremaschi *et al.* also cited that high oil retention reduces the COP and the cooling capacity of the system.

Allgood and Lawson (2010) investigated the behavior of R438A as a replacement for R22 in refrigeration and air conditioning systems. The authors recommended changing the elastomeric seals in the retrofitted systems because of the higher risk of leakage. Due to the high viscosity of R438A/MO in the retrofitted system, a good oil circulation rate was difficult to achieve. Therefore, it was suggested to add a small amount of hydrocarbon (HC) to the refrigerant to reduce the viscosity, especially at lower temperatures. The high viscosity is a result of the low solubility of hydrofluorocarbons (HFC) in mineral oil and the fact that HFC and MO is a non-miscible mixture. To increase the overall solubility, the use of 10-20% of POE, which is added to the mineral oil, is suggested. This improved the oil return and decreased the potential of oil trapping in liquid receivers. The study showed that the oil level in the compressor stayed constant over a period of three weeks using a mixture of R438A as refrigerant with 80% MO / 20% POE, and without using an oil separator.

Zoellick and Hrnjak (2010) studied the oil retention in horizontal and vertical suction lines using R410A/POE. Unlike the studies of Cremashi et al., the oil was injected directly into the liquid refrigerant to create a more homogeneous mixture. It was proposed to avoid churn flow in the suction line, which resulted in excessive oil hold up. It was recommended that the system works above the Jacobs limit at all times. This is important because hysteresis in the transition between churn and annular flow was observed. Higher mass flux is needed for the transition from churn to annular flow than from annular to churn flow. It was also observed that increasing the superheat increased the oil retention due to the higher amount of evaporated refrigerant. Due to the higher amount of evaporated refrigerant the concentration of oil in the liquid phase refrigerant increased, thereby increases the film viscosity. Similar to Cremashi *et al.*, a strong relation between oil circulation ratio and oil retention was found.

In the scope of this study, four different refrigerants, namely R407C, R22, R438-1, and R438-2, were tested and the quantity of oil flowing back to the compressor was investigated. The findings were compared to the R22 test results, which served as a baseline. The measurements were conducted using a residential split-system air conditioning unit with a cooling capacity of 8.5 kW. The test stand was designed and built to investigate how much oil circulates in a residential split system using alternative refrigerants. Therefore, a test section was designed to collect and measure the oil return in the compressor suction line based on the assumption that the compressor has a oil circulation rate of 1 wt%. The test section consists of an oil separator, a vessel for oil collection, and a fluid level sensor for measuring the collected oil volume.

2. EXPERIMENTAL SET-UP

2.1 Test Setup

The test system consists of an outdoor unit and an indoor unit, which are connected by suction and liquid lines. The outdoor unit (*Haier Model HC30D2VAR)* contains a reciprocating compressor (*Bristol Model H21J24BABCA)*, a fin and tube condenser, and a fan. In the liquid line a sight glass is installed in front of a Coriolis mass flow meter (*Micro Motion F Series*), to visually check if the refrigerant is in the liquid state before entering the mass flow meter. After that, an indoor air handler with a fixed orifice (*NORDYNE Model B6BMM030K)* is used. The oil measurement section consists of a helical oil separator (*Henry Technologies*), a sight glass, and an oil level probe under the oil separator. After the oil measurement section, the suction line connects back to the compressor. A system schematic is shown in Figure 1. The test setup is equipped with temperature and pressure sensors and a data acquisition system. Detailed information of the sensors can be seen in Table 1.

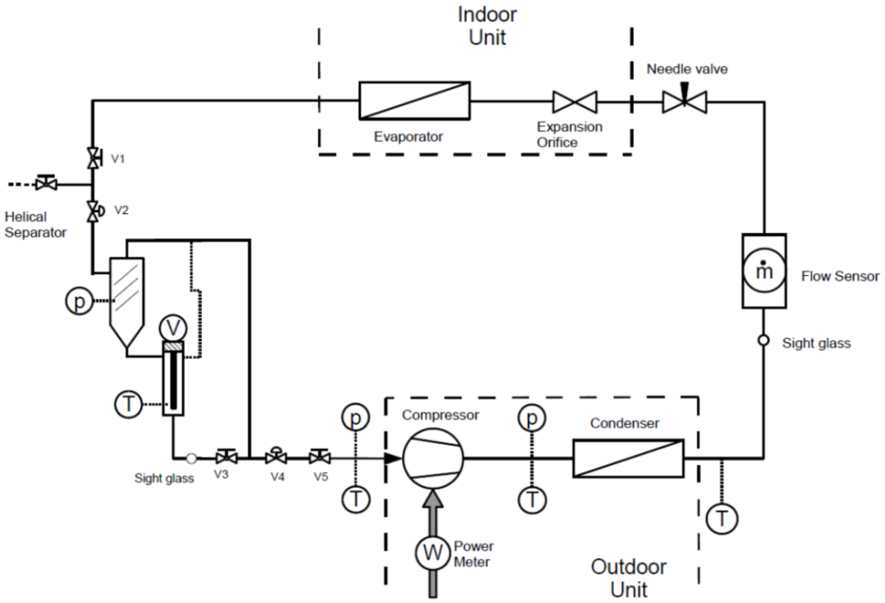

Figure 1. Schematic of the test setup

2.2 Instrumentation

The test stand is equipped with in-stream thermocouples (T) and absolute pressure sensors (P) at the inlet and outlet of the compressor and at the oil separator. The temperature of the subcooled refrigerant is measured by a thermocouple on the pipe surface of the liquid line in front of the sight glass and the Coriolis mass flow meter ($\dot{m}$). All sensor signals are logged by a data acquisition system, *National Instrument Model cDAQ9174,* which is connected to a computer running *LabVIEW 2013*.

The absolute pressure sensors have been calibrated before installation and the ambient pressure was compensated by *LabVIEW*. Table 1 shows the sensors and measurement uncertainty of the employed measurement devices.

Table 1: List of Sensors names, types, and uncertainties

Name	Measurement device	Uncertainty
Suction Temperature Discharge Temperature Oil Temperature Liquid Line Temperature	Thermocouple Type T Thermocouple Type T Thermocouple Type T Thermocouple Type T	± 0.5 C
Suction Pressure Discharge Pressure Oil Pressure	Setra 207 0-250 psi Setra 207 0-250 psi Setra 207 0-250 psi	± 0.022 bar
Mass Flow	Emerson Micro Motion F025P	± 0.2% of rate (liquid mass flow)
Power Consumption Compressor	Scientific Columbus XL5C5A2	± (0.2%Reading + 0.01% RO) RO…Rated Output

2.3 Refrigerants

Four different refrigerants were tested in this study. Table 2 shows the specification of the tested refrigerants. The GWP[1] is calculated based on the weighted average GWP's of the individual components (U.S. Environmental Protection Agency, 2015). The temperature glide, saturation pressure (P_{sat}), and critical temperature (T_c) were calculated using *REFPROP (*Huber *et al.* 2013*).* As the system was initially built for R22, R22 tests were considered as baseline results. For the baseline tests, an oil mixture of 95% MO and 5% POE was used.

The two R438 blends used in this study contain different concentrations of propane (R290). Propane belongs to the group of hydrocarbons (HC), which provides a higher solubility in mineral oil and decreases the viscosity of the oil. Other alternatives, such as R422D or R438A, use R600 (n-Butane), which is also a hydrocarbon. Allgood and Lawson (2010) have also suggested adding small amounts of HC to decrease the viscosity of the oil.

Table 2: Specification of the refrigerants

Name	GWP[1] [-]	Temperature glide @ 10 bar [°C]	Fluid Density @10 bar [kg/m3]	Latent Heat @ 10bar [kJ/kg]	P_{sat} @ 45 °C [bar]	T_c [°C]
R22	1810	0	1196.8	184.31	17.3	96.16
R407C	1774	5.6	1164.1	192.61	17.5/19.7	86.16
R438-1	2265	7.0	1165.5	167.45	17.7/20.1	81.96
R438-2	2295	5.9	1185.1	164.87	17.3/19.4	82.92

3. METHODOLOGY

3.1 Test Procedure

All tests were performed at ambient temperature for the indoor and outdoor units, which was 21.5 ± 1.5°C. The ambient temperature and humidity was controlled by the air conditioning system of the laboratory.

A detailed test procedure was developed to assure that all tests were conducted according to the same operating conditions. To increase the measurement accuracy the refrigerant has to be properly subcooled before entering the mass flow meter. To guarantee the system performance, the refrigerant has to be in a liquid state at the inlet of the expansion device. Therefore the subcooling temperature was taken as reference.

The subcooling is only adjustable by the amount of refrigerant in the system, and is influenced by the expansion valve characteristics and ambient temperature. The same charging procedure was applied for all tested refrigerants:

- Step 1: The system was charged with 3 kg of refrigerant
- Step 2: The needle valve is opened two turns and the system is switched on.

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[1] GWP: Global Warming Potential. The GWP is expressed as a factor of CO_2, whose GWP is 1.

- Step 3: The needle valve is adjusted until the system reached 10 °C of superheat.

If the subcooling was too low after pre-charging, more refrigerant was added to the circuit in small steps until the subcooling temperature reached the desired conditions, while the system was running under steady state conditions. This procedure was repeated until the superheat was approximately 10°C and the subcooling was about 7.5°C.

Two different tests were conducted using the test stand: the 1st test was a 6 min, 10 min, and 15 min runtime test and 2nd test was 90 min runtime test.

During the first tests, the system was in operation until it reached steady state conditions. Then, the valve V3 was closed and the timer was started. After reaching the test time, the system was switched off. To prevent liquid refrigerant flowing into the measuring vessel, the valves V1 and V5 were closed. After the system was switched off, measurements were taken after a couple of minutes so that the oil could drain from the separator into the measuring cylinder. After the measurements were completed, the system was turned on again and all valves were opened to return the collected oil back to the compressor.

During the second test series (90 min runtime tests), the test procedure was the same as for the 1st test, except for one point. When the system was switched off, all refrigerant was recovered and the collected oil was drained from the bottom of the measurement vessel. Further details about the testing are explained in the next chapter.

4. EXPERIMENTAL RESULTS

4.1 6 min, 10 min and 15 min Runtime Test Results

Unfortunately, no oil was collected during the 6 min, 10 min, and 15 min runtime tests using the refrigerants listed in Table 2. The most likely causes are:

- The oil circulation rate (OCR) was extremely low, which could lad to a lower efficiency of oil extraction and to a very low amount of oil.
- The oil was trapped somewhere else in the system and never reached the oil separator in the suction line.

A low OCR reduces the quantity of the extract oil out of the vapor refrigerant, especially if it is well mixed. Cremaschi *et al.* (2005) used a special test setup in their study where they were able to measure the oil retention of different components of the refrigeration system. As part of their study, the authors injected a certain amount of oil at different locations of the system and the oil was extracted in the suction line. The oil was extracted using a helical oil separator, as in the tests of the present study. The efficiency of extraction was calculated based on the difference between injected and extracted oil. It was concluded that the efficiency of oil extraction was between 95% to 99% for OCRs equal or greater than 5 wt%. However, the efficiency dropped below 50% when the OCR was less than 1 wt%. This could be the reason why the oil separation within the current project behaved similarly, which could mean that the efficiency of oil extraction in the suction line is under 50%. Assuming a low OCR of 0.5wt%, an extraction efficiency of 25%, and a mass flow rate of 0.04 kg/s, 45 g of oil should have been collected after 15 minutes. However, that was not the case.

Another cause for the absence of oil during the short run-time tests was most likely due to oil being trapped somewhere within the test setup circuit. Even running the system with R22, no oil was collected by the oil separator in the suction line. This result indicated that oil was transported to the heat exchangers but the running time of the system was too short for the oil to return to the compressor. During the short run-time tests, the compressor power consumption was constant, which indicated that the compressor had enough oil. If the lubrication of the compressor was not adequate the power consumption would have increased over time.

Since no measurable amount of oil was collected within the 6 min, 10 min, and 15 min run-time tests, it was decided to run the system for a longer time, e.g. 90 minutes, with the goal to collect at least a measurable amounts of oil.

4.2 90 min Run Time Test Results

A 90 min runtime test series was performed to collect measurable amounts of oil at the oil separation section of the test setup. After 90 min, the amount of collected oil was very low and could not be measured using the oil level probe. The oil was drain from the bottom of the oil vessel and weight after each test run. An advantage of draining the oil was that the collected oil could be weighted externally with a precise laboratory balance (A&D HR 100-AZ). A second advantage was the smaller amount of dissolved refrigerant inside the oil.

After each 90 min test, the refrigerant was recovered, and the oil was drained from the vessel and measured. All connections of the test setup and the sight glass were inspected carefully so that no oil was trapped in the oil collection section. For next test, the system was evacuated and then charged with new refrigerant.

4.2.1 R22 Test Results

The system was charged with 3.43 kg of R22, which was less than for the short test runs. That explains the slightly lower superheat compared to the short test runs. Figure 2 shows the pressure, temperature and mass flow rate measurements during the 90 minutes test. At the end of the test run, a small amount of oil was seen in the sight glass. When the system was opened, 3.9 g of oil were drained.

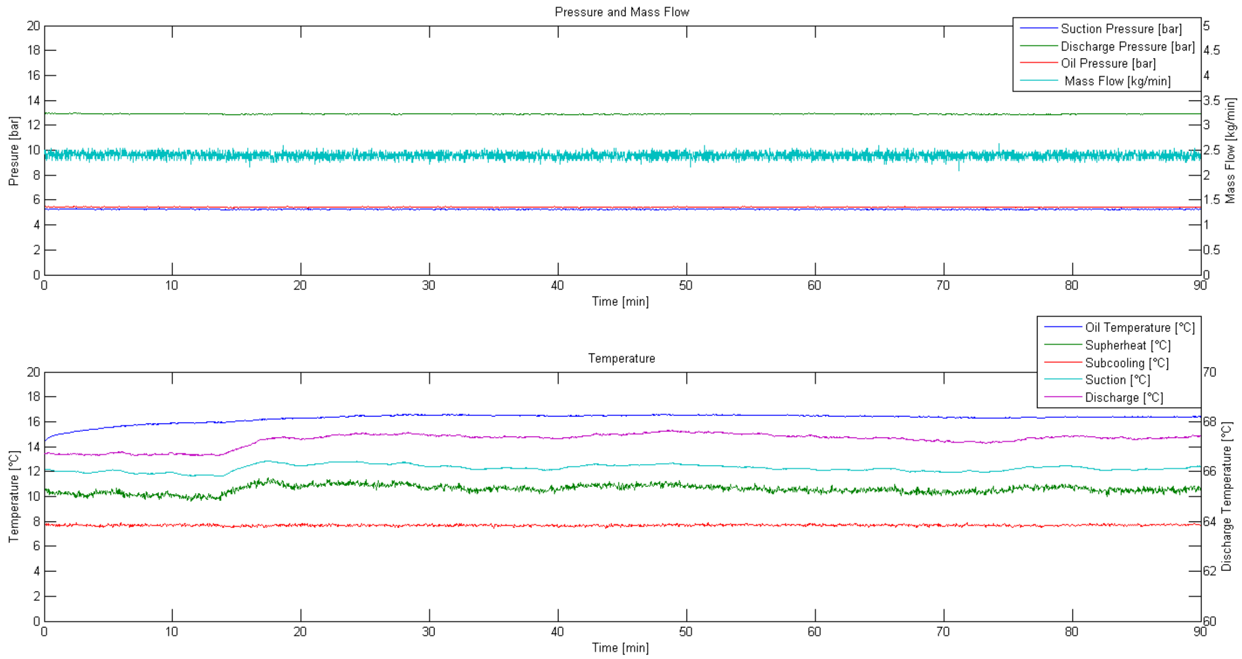

Figure 2: Steady state readings of the 90 minutes test run with R22 at an average superheat of 10.6 °C

4.2.2 R407C Test Results

Figure 3 shows the results of the 90 min test run using R407C as refrigerant. During the test, the superheat was slowly decreasing. To prevent the superheat dropping below 10°C, the needle valve was slightly closed, which resulted in a jump of the superheat of more than 2°C. This illustrates clearly how sensible the superheat was as a function of needle valve changes. During the whole test, the oil level probe did not detect any oil and no oil was seen in the sight glass. When the system was drained, this observation was further confirmed. No measurable oil was collected from the oil separator section.

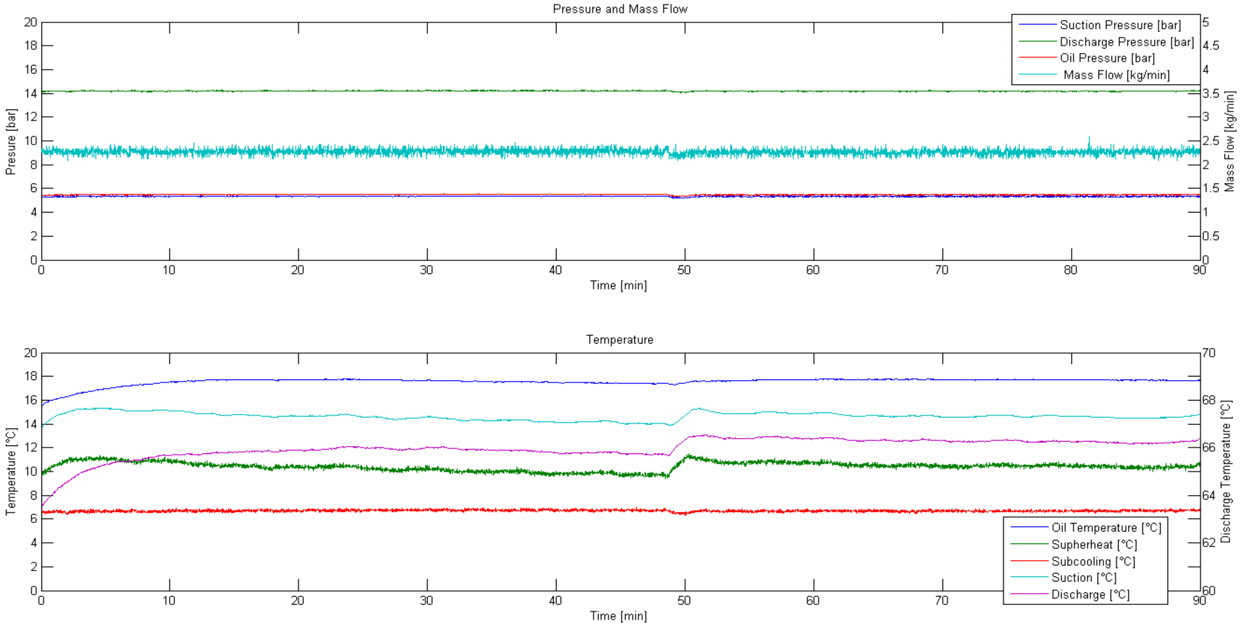

Figure 3: Steady state readings of the 90 minutes test run with R407 at an average superheat 10.4 °C

4.2.3 R438-1 Test Results

Figure 4 shows the measured values for the 90 min test run using R438-1. At the beginning, the superheat was fluctuating, which was caused by over-steering the needle valve. During the test run, no oil appeared in the sight glass. However, when the system was drained, 2.9 g of oil were collected.

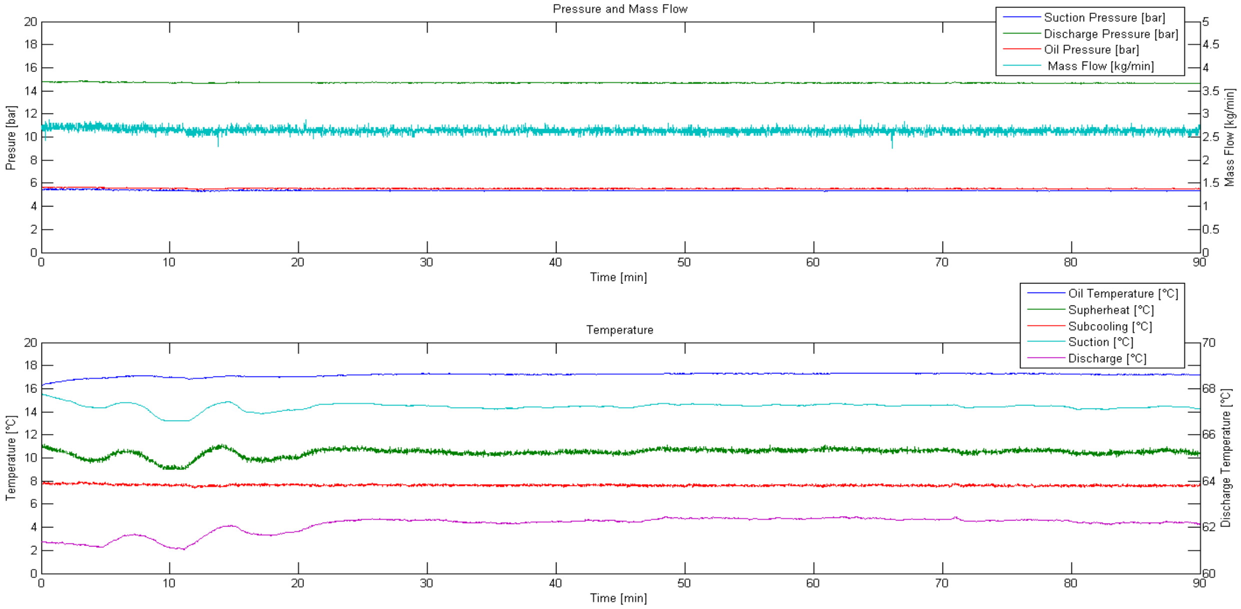

Figure 4: Steady state readings with R438-1 for 90 minutes at an average superheat 10.47 °C

4.2.4 R438-2 Test Results

Figure 5 shows the measured process parameters during the 90 minutes run-time test with R438-2. There is a drop of the superheat at the beginning, which was regulated by adjusting the pressure drop across the needle valve. After 90 minutes, no oil was seen at the sight glass. When the system was drained, 0.5 g of oil were collected.

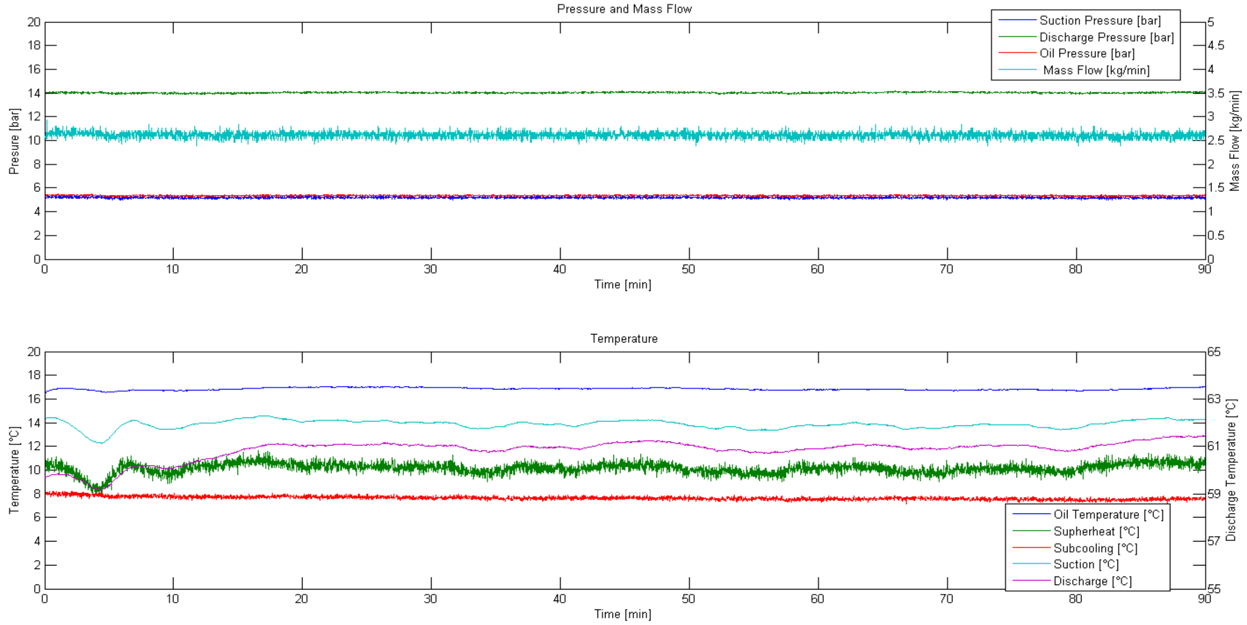

Figure 5: Steady state readings of the 90 minutes test run with R438-2 at an average superheat 10.2 °C

5. CONCLUSIONS

An experimental test setup was designed and built to measure the mass of oil flowing back to the compressor. Four different refrigerant/oil mixtures were tested. The results showed little differences in the measured oil return for the four refrigerants. During the tests, the oil inside the refrigeration system did not change. It consisted of 95% mineral oil with 5% polyol ester oil. During the 6 min, 10 min, and 15 min test runs, no oil was extracted out of the suction line. During the 90 min run-time tests, small amounts of oil were collected, as shown in Table 3.

Table 3: Collected oil amounts and system performance during 90 min runtime test.

Refrigerant	**Refrigerant Charge [kg]**	**Collected Oil [g]**	**Pressure Ratio [-]**	**COP [-]**	**Comp. Power Input [W]**
R22	3.43	3.9	2.45	4.61	1521
R407C	3.60	-	2.66	4.14	1621
R438-1	4.02	2.9	2.74	4.05	1655
R438-2	3.99	0.5	2.71	4.12	1602

3.9 g of oil were collected while using R22 as refrigerant in the test stand. No oil was collected when using R407C. Changes of the collected amount of oil using the R438 blends are a result of the propane concentration in the mixture. More propane reduced the viscosity, which could lead in a higher oil flow back to the compressor. 2.9 g of oil were collected when R438-1 was used as the refrigerant, which has a higher concentration of propane compared to R438-2. Nevertheless, a slight performance difference between the refrigerants was detected during the 90 min runtime test. The main conclusions of the study are:

- R22 shows the highest oil return behavior with the used oil mixture of 95% MO and 5% POE.
- No oil was detected with R407C, which corresponds to the expectation of low oil return due the low miscibility with the used oil mixture.
- R438-1 shows a higher amount of returned oil compared to R438-2, which could be attributed to the higher amount of R290 in R438-1.
- The COPs achieved with the R438 blends are almost identical as the one for R407C.

- The density and latent heat of the R438 mixtures are lower than for R407C, which could lead to the lower cooling capacities.
- The test results fit the expectations of oil return and show that the drop-in refrigerant R438-1 could be suitable to retrofit existing R22 systems.

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ACKNOWLEDGEMENT

We gratefully acknowledge the support of our project sponsor *BMP International Inc*. and particularly we like to express our gratitude to Mr. Ben Meng. We also thank Mr. Frank Lee for the help with the test setup.